CHAPTER 21

ELECTRO MAGNETISM

The magnetic field created by a bar magnet may be duplicated by passing current through a suitable arrangement of conductors. The advantage of this method is that the strength of the magnetic field can be controlled, whereas the strength of the magnetic field of a bar magnet is constant. Some of the factors which control the strength of magnetic fields are discussed in this Chapter.

21.1 MAGNETIC FIELDS AROUND A CONDUCTOR

The movement of electrons in a conductor always creates heat and a magnetic field. The magnetic field in a straight conductor carrying current consists of a series of concentric circles around the conductor. (Figure 21.1).

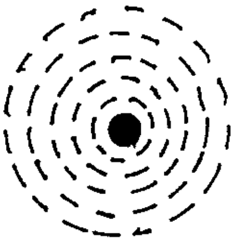

Figure 21.1

The direction of current in a conductor which has been cross-sectioned is indicated by a cross or a dot. A cross means that current is travelling away from the observer while the dot shows the current is towards the observer. (Figure 21.2).

Figure 21.2

The direction of the magnetic field around the conductor is determined by placing the fingers of the right hand around the conductors with the thumb pointing in the direction of the current. The fingers indicate the direction of the magnetic field. (Figure 21.3).

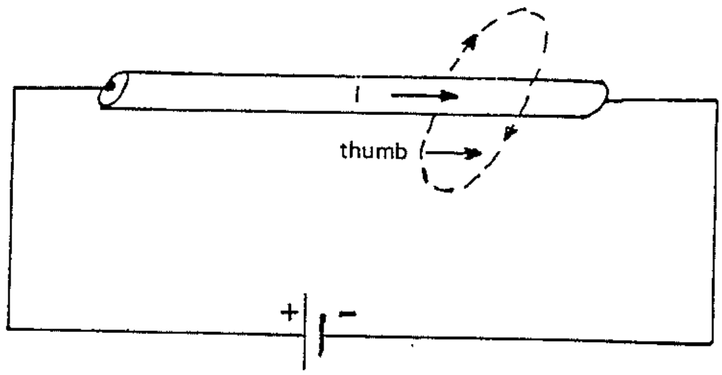

Figure 21.3

When two current carrying conductors run parallel and adjacent to each other the magnetic fields shown in Figure 21.4 result.

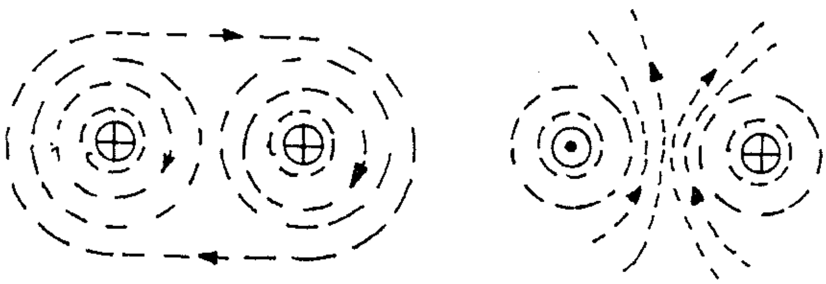

Figure 21.4

A repelling force exists between conductors whose currents are in the opposite direction, while forces of attraction exists between conductors whose currents are in the same direction. In Chapter 19 it was stated that excessive currents could physically damage equipment. This damage often results from the stresses set up by the magnetic fields that are created around the conductors by these excessive currents.

21.2 THE SOLENOID

A solenoid is formed when a length of conductor is wound into a coil. The effect of winding the wire in this manner is to concentrate the lines of force of the magnetic field, so that they all pass through the centre of the solenoid. Lines of force are continuous (Chapter 20), so they must pass around the outside of the coil to again link up with the lines passing through the centre of the solenoid. A solenoid is an electromagnet, the magnetic field only existing while current is in the conductors. When current ceases, the magnetic field decreases to zero. The direction of the field in a solenoid is determined by placing the fingers of the right hand around the solenoid in the direction of current flow. The thumb of the right hand then indicates the north pole of the solenoid. (Figure 21.5).

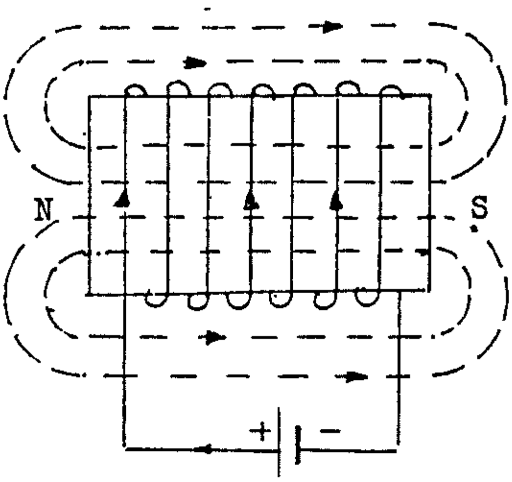

Figure 21.5

All the laws that apply to the magnetic field of a bar magnet also apply to the field of an electromagnet. Because the lines of force are directed around the solenoid (by forming the wire into a coil) the path of the lines of force is called a magnetic circuit.

21.3 THE MAGNETIC CIRCUIT

The magnetic circuit may be likened to an electrical circuit. The magnetic field requires a magnetomotive force (F) to build up a field. It has opposition, called reluctance (S), to the building up of this field, and a resultant number of lines of force called the flux (Φ). These may be likened to the e.m.f., the resistance and the current respectively in the electrical circuit.

The magnetomotive force (abbreviated to m.m.f.) has the units of ampere (turns) (At). The m.m.f. is directly proportional to the current and the number of turns in a solenoid. The reluctance of a magnetic circuit has the units of ampere turns per weber (At Wb^{-1}). The weber is the unit for measuring the flux (Φ) of the magnetic field. Using the analogy of the electrical circuit ($I = \frac{E}{R}$) the equation for the flux of a magnetic circuit is, $\Phi = \frac{F}{S}$ webers.

Example 21.1

Five amperes flows in a coil which has 2000 turns. If the reluctance of the magnetic circuit is 1.2×10^6 ampere (turns) per weber, calculate the flux of the magnetic circuit.

$F = 2000 \times 5 = 10000$ ampere (turns)

$S = 1.2 \times 10^6$ At Wb^{-1}

$\phi = ?$ Wb

$$\phi = \frac{F}{S} = \frac{10000}{1.2 \times 10^6} = 0.0083 \text{ Wb}$$

Example 21.2

Calculate the current required in a coil of 1000 turns to produce a flux of 0.001 weber if the magnetic reluctance of the coil is 1.5 x 10^6 ampere turns per weber.

Φ = 0.001 Wb

S = 1.5 x 10^6 AT Wb^{-1}

N = 1000

I = ? A

$$\Phi = \frac{N\,I}{S}$$

$$I = \frac{\Phi S}{N}$$

$$= \frac{0.001 \times 1.5 \times 10^6}{1000}$$

$$= 1.5 \text{ A}$$

The reluctance of a magnetic circuit has been said to act on the magnetic circuit in a similar manner to resistance in an electrical circuit. An increase in the length of a magnetic circuit results in an increase in the reluctance of the circuit, while an increase in the cross-sectional area of the magnetic circuit results in a decrease in the reluctance of the circuit. (Note the similarity to resistance of conductors). Reluctance is directly proportional to length (l) and inversely proportional to the cross-sectional area (A). In Chapter 20, the term permeability (μ) was used to describe the ability of a material to allow the building up of lines of force. The magnetic field of a air cored coil has only the air through and around the coil to act as a conducting medium for the magnetic field. The permeability of air is very low. (Table 20.1) If an iron core is placed in the centre of the coil and the m.m.f. kept constant the high permeability of the iron will allow many more lines of force to be built up in the magnetic circuit. The magnetic circuit now consists of the iron core in the centre of the coil plus the air circuit on the outside of the core (Figure 21.6). The total reluctance of the magnetic path has been reduced by the introduction of the iron core.

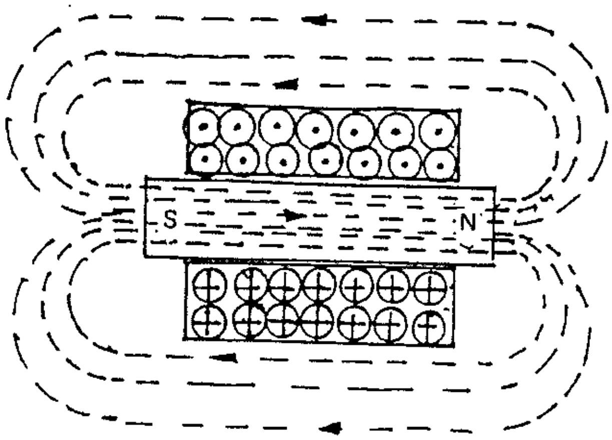

Figure 21.6

When the iron in the circuit is increased so that it completely replaces the air path around the coil, the reluctance of the circuit will be further reduced as the lines of force will take the path of the iron, with its high permeability, in preference to that of the surrounding air. (Figure 21.7).

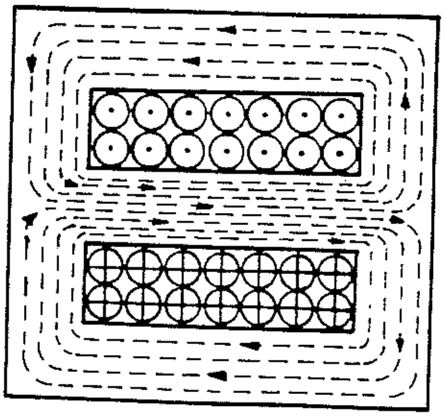

Figure 21.7

As the flux created by a constant m.m.f. in the solenoid has increased with the introduction of the high permeability material, the reluctance of the magnetic circuit must have decreased. From this is can be seen that the reluctance of the circuit is inversely proportional to the permeability of the circuit. Equating the three factors governing the reluctance of a circuit the reluctance $S = \frac{l}{\mu A}$ At Wb^{-1}.

Table 20.2 gives a comparison of the permeabilities of different materials compared with the permeability of air, which is given a base figure of unity (1). The permeability in the reluctance equation is made up of two factors –

1. The permeability of free space (μ_o), which is $4 \pi \times 10^{-7}$ (a constant).

2. The relative permeability of a material (μ_r) which is given in the Table 20.2.

Hence, $\mu = \mu_o \times \mu_r$ and the reluctance equation becomes –

$$S = \frac{l}{\mu_o \mu_r A} \text{ At } Wb^{-1}$$

Where -

S = ampere turns per weber
l = metres
A = metres squared
μ_o = $4 \pi \times 10^{-7}$
μ_r = relative permeability (a ratio)

Example 21.3

A magnetic circuit is 250 millimetres long and has a cross-sectional area of 400 millimetres squared. If the circuit is constructed of steel which has a permeability of 10000, calculate the reluctance of the circuit.

$l = 250 \times 10^{-3}$ m
$A = 400 \times 10^{-6}$ m^2
$\mu_o = 4 \pi \times 10^{-7}$
$\mu_r = 10000$

$$S = \frac{l}{\mu_o \mu_r A}$$

$$= \frac{250 \times 10^{-3}}{4 \times \pi \times 10^{-7} \times 10000 \times 400 \times 10^{-6}}$$

$$= 0.49 \times 10^{6} \text{ At } Wb^{-1}$$

21.4 FLUX DENSITY

A solenoid may be air cored or may have a core of magnetic material. The air cored solenoid is used extensively in the electronic area, but most solenoids used in the applied electricity field are iron cored to increase their magnetic effect. Besides the total flux a magnetic circuit may build up, it is necessary to know the concentration of the lines of force per unit area, as the cross-sectional area of the circuit may need to be varied. The lines of force per unit area is called the flux density (B) and has the unit of webers per metre squared (Wb/m^2). A weber per metre squared is known as a 'tesla' (T).

$$B = \frac{\Phi}{A} \text{ tesla}$$

Example 21.4

A magnetic circuit has a cross-sectional area of 1500 millimetres squared and a total flux of 0.001 weber. Determine the flux density of the circuit.

Φ = 0.001 Wb
$A = 1500 \times 10^{-6}$ m^2
B = ?

$$B = \frac{\Phi}{A}$$

$$= \frac{0.001}{1500 \times 10^{-6}}$$

$$= 0.66 \text{ T}$$

Example 21.5

A magnetic field of 1.5 tesla exist in an iron circuit whose c.s.a. is 5 mm^2. Calculate the flux of the magnetic field.

$B = 1.5T$

$A = 5 \times 10^{-6} m^2$

$\Phi = ?\ Wb$

$B = \frac{\Phi}{A}$

$\Phi = BA$

$= 1.5 \times 5 \times 10^{-6}$

$= 7.5 \times 10^{-6} Wb$

21.5 FORCE ON A CONDUCTOR

When a current carrying conductor cuts the lines of force of a stationary magnetic field, a force will be exerted on the conductor. (Figure 21.8).

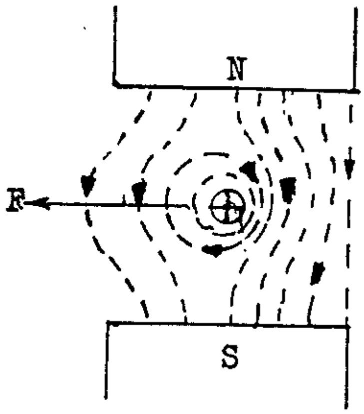

Figure 21.8

It will be noted that the lines of force on the left hand side of the conductor oppose each other while the lines of force on the right hand side have the same direction. Under these conditions there is a weakening of the field on the left hand side of the conductor and a strengthening of the field on the right hand side of the conductor. This strengthening of the field exerts a force on the conductor in the direction indicated. The magnitude of the force (F) is proportional to the strength of the stationary field (B) the length of the conductor passing through the field (l) and the instantaneous current in the conductor (i).

$F = B\, l\, i$ newtons

Where –

F = force in newtons (N)

B = flux density in tesla (T)

l = length in metres

i = current in amperes

Example 21.4

A conductor, 200 millimetres in length carries a current of 10 amperes when intersecting a magnetic field whose flux density is 0.9 tesla. Calculate the force on the conductor –

$B = 0.9\ T$

$l = 200 \times 10^{-3}\ m$

$i = 10A$

$F = ?N$

$F = B\, l\, i$

$= 0.9 \times 200 \times 10^{-3} \times 10$

$= 1.8\ N$

The force produced by the interaction of two magnetic fields is used to produce a turning motion or torque (T) on a conductor free to rotate through the field. A conductor located at a radius (r) from a pivot point in a magnetic field will experience a torque $T = F\ r$ newton metres. (Figure 21.9).

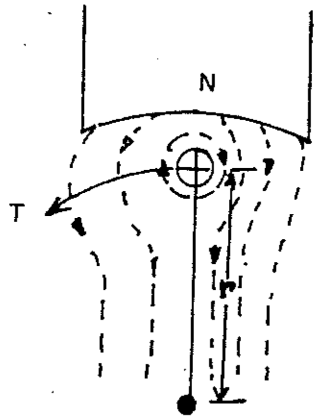

Figure 21.9

Example 21.5

A current carrying conductor which is 250 millimetres from a pivot point experiences a force of 2 newtons when placed in a magnetic field. Calculate the torque produced on the conductor.

$F = 2$ N

$r = 250 \times 10^{-3}$ m

$T = ?$ Nm

$T = F\ r$

$= 2 \times 250 \times 10^{-3}$

$= 0.50 \times 10^{-3}$ Nm

The force and torque produced on a current carrying conductor by a stationary magnetic field, are utilised in electric motors and meters.

Equations in this chapter

(1) $\Phi = \frac{F}{S}$

(2) $S = \frac{l}{\mu A}$

(3) $S = \frac{l}{\mu_0 \mu_r A}$

(4) $B = \frac{\Phi}{A}$

(5) $F = B\ l\ i$

(6) $T = F\ r$

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(1) A magnetic circuit has a c.s.a. of 360 mm^2 and a length of 300 mm. If the relative permeability of the steel is 5000, calculate the reluctance of the iron circuit.

(2) Calculate the force applied to a conductor 500 mm in length, which intersects a magnetic field whose flux density if 0.25 tesla while it is carrying 7.5 amperes.

(3) Determine the flux density in an iron circuit whose c.s.a. is 500 mm^2 and has a total flux of 0.01 weber.

(4) Determine the total flux produced by a coil of 1000 turns carrying a current of 1.5 amperes if the reluctance of its iron circuit is 0.75×10^6 At/Wb.

(5) What force would be required from a conductor 250 mm from a pivot point to produce a torque of 0.001 Nm